

# **Geology of the Greens Creek Mining District**

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Chapter 4 of

**Geology, Geochemistry, and Genesis of the Greens Creek Massive Sulfide Deposit, Admiralty Island, Southeastern Alaska**

Edited by Cliff D. Taylor and Craig A. Johnson

Professional Paper 1763

**U.S. Department of the Interior  
U.S. Geological Survey**

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4-1. Geology of the Greens Creek mine area.



# Geology of the Greens Creek Mining District

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## Abstract

The Greens Creek polymetallic sulfide deposit occurs within the low-grade metamorphic core of the Admiralty subterrane of Alexandria. Local tectonostratigraphic assemblages constitute late Paleozoic back-arc basement and its Upper Triassic flood basalt cover sequence. The Admiralty back-arc basin was volcanically active into the Devonian, giving rise to Retreat Group greenstones. The Upper Devonian through Lower Permian Cannery Formation includes older deep marine siliciclastics and a younger shallow marine dolomite-chert facies. The uppermost Pybus Formation signals the termination of back-arc sedimentation through shoaling accompanying the amalgamation of Alexandria and Wrangellia by the mid-Permian. The post-amalgamation unconformity ended with Late Triassic rifting driven by the Nikolai plume: the Carnian Nikolai Greenstone and Norian Hyd Group flood basalt provinces, occurring respectively in Wrangellia and Alexandria, overlap in time. The Greens Creek deposit is hosted within Carnian/Norian-age black argillite occurring below the Hyd basalts.

Protracted compressional tectonism attended the suturing of the Wrangellian superterrane to continental North America. Mid-Cretaceous collision resulted in fold and thrust-style imbrication, while dextral transpression on the Tertiary Denali transform system caused severe strike-slip dislocation of the imbricated stratigraphic package. The back-arc assemblage and its flood basalt cover were decoupled, resulting in a stacked series of inversely metamorphosed thrusts south of the mine. The Greens Creek deposit occurs in low-grade phyllites, which make up the lowest exposed thrust plate. This mineralized domain is bound by major ductile faults bordering on Hawk Inlet and Young Bay. Brittle northwest-southeast fault fracture systems are common; the Maki fault through the immediate mine site dextrally offsets the mineralization about 1,800 feet.

The Hyd Group is subdivided informally into basal growth-fault-related breccia/conglomerate, medial mine argillite, and upper basalt members. At the mine, the Retreat Group greenstone substrate to mine argillite is interleaved with sheets of serpentinite and lesser metagabbro. Intense hydrothermal alteration of this rock association forms the informal mine phyllite in the stratigraphic footwall of the ore. Widespread occurrence of barian mariposite ties hydrothermal alteration of serpentinite to massive baritic ores capping mine phyllite. High-grade laminated ores at the

base of mine argillite are capped by bedded pyrite, and thin, cherty, black manganoan dolomite beds persist into overlying slaty argillite.

Greens Creek is unique in that it comprises high-grade zinc-lead-silver-gold ores at a major unconformity in a juvenile arc setting. The deposit is linked to an active rift segment plumbed by serpentinite/gabbro and filled with euxenic pyritic-graphitic argillite. Gabbro sills intruding mine argillite have the same geochemistry as the upper Hyd Group basalt, thus tying rifting to the Nikolai plume. Although somewhat of a volcanogenic massive sulfide/sedimentary exhalative hybrid, the Greens Creek setting lacks the felsic volcanics that characterize polymetallic Kuroko-type volcanogenic massive sulfide districts. The link to a growth-fault-controlled, starved sedimentary trough makes it more appropriate to classify Greens Creek as a sedimentary exhalative deposit.

## Introduction

The Greens Creek polymetallic (Zn-Pb-Ag-Sb-As-Cu-Au-Ba) sulfide deposit, the location of which is shown on plate 1 (plate 1 in digital form only), occurs in complexly deformed, low-grade phyllites exposed between Hawk Inlet and Young Bay on northern Admiralty Island. The mine is situated in the upper reaches of Greens Creek, outcropping as a gossanous kill zone on the west wall of the Big Sore tributary. This chapter describes the district geology of the Greens Creek mining area, extending from the cirque headwall of Cliff Creek, approximately 3 miles southeast of the mine, through the Zinc Creek drainage northeastward to the isthmus separating Hawk Inlet and Young Bay. The geological overview covers an approximate 10-mile-long segment of the northwest-trending phyllite belt on strike with the mine. The road connecting the mine to accommodation facilities on Hawk Inlet and docking facilities on Young Bay provides the most accessible transect through the complex tectonostratigraphy of the area (fig. 1). Because the mine is within the Admiralty Island National Monument, surface exploration is restricted to lands specified by a Federal land-exchange agreement dating from 1995, together with the area immediately to the north through the Lil Sore Creek drainage that is covered by Federal Mining Lode Claims. A total of 119 square miles is open to mineral exploration.



**Figure 1.** Lodging facilities at Hawk Inlet.

Geological mapping in this area is severely hampered by rugged mountainous topography, a near-complete veneer of glacial till, and dense vegetation below ridge crests. Ridges provide the best exposures, with common rocky knobs outcropping through thin, clayey basal till. The steep U-shaped valley walls and heavy foliage, including patches of devils club wherever sunshine penetrates the canopy formed by old-growth stands of hemlock and spruce, restrict helicopter access largely to ridge crests. Muskegs that develop over the larger serpentinite bodies offer a few additional landing sites. The thickness of till cover increases downslope, with almost no bedrock exposure except on truncated spurs forming cliff faces and along deeply incised stream courses. Although creek traverses from ridge crests to valley floors are physically taxing, these provide the most effective means of attaining bedrock information.

The district geological map (plate 1) is based on 1-inch to 500-foot scale mapping carried out over most of the area shown and documented in unpublished Greens Creek Mining Company reports. The compilation incorporates data collected since the discovery of the Greens Creek deposit in the mid-1970s (fig. 2). This information has been reinterpreted in the light of airborne geophysical surveys carried out in 1995–96. The core of the area, including upper Cliff Creek, the Greens Creek mine site, Mammoth Ridge to Killer Creek, and the Zinc Creek and Lil Sore Creek drainages, has been mapped in greatest detail. The geology shown for outlying areas is less detailed but is included to provide a broader context for situating the mine stratigraphy.

This chapter describes the district geological setting of the Greens Creek ore deposit. Results from limited supporting microscopy and geochemistry are reported; however, lithological subdivision is based essentially on field observations. We refine the Retreat-Cannery-Hyd tectonostratigraphic grouping based on earlier reconnaissance mapping by the U.S. Geological Survey (Lathram and others, 1965). The main objective is to define the structural-stratigraphic controls of the Greens Creek ores. The second section of this chapter presents a regional geotectonic framework for the district. The third section provides brief lithological descriptions and an overview



**Figure 2.** Big Sore, the discovery site of the Greens Creek deposit.

of the local structural/stratigraphic relationships of the various rock units. The fourth section describes the mine-site geology and places several prospects within their geological framework. The fifth section offers a number of hypotheses concerning the genesis of the Greens Creek deposit, based on observed ore/host-rock relationships.

## Regional Geotectonic Framework

Admiralty Island occupies a central position in the Alexander Archipelago and is the type locale for the Admiralty subterrane of the Alexander terrane (Alexandria). Alexandria formed as a Late Proterozoic-Paleozoic oceanic island arc system somewhat older than the late Paleozoic Wrangellian oceanic island arc system with which it had amalgamated by the Permian (Berg and others, 1978; Gehrels and Saleeby, 1987a; Gardner and others, 1988; Karl and others, 1999a). On Admiralty Island, 265-Ma (*mega-annum*) metamorphic dates (Karl and others, 1999b; Haeussler and others, 1999) and a regional mid-Permian to Late Triassic unconformity record the time of amalgamation. The 50-Ma period of nondeposition following this event ended in the Middle to Late Triassic with rift-related flood basalt volcanism caused by the Nikolai Greenstone plume (Richards and Jones, 1991).

Recent geochronology (S.M. Karl, oral commun., 2002) identifies substrate on Admiralty Island dating back to the Late Proterozoic, thus linking the Admiralty subterrane to the Craig subterrane, which includes similar-aged Late Proterozoic and Paleozoic arc volcanics on Prince of Wales Island (Gehrels and Saleeby, 1987b). The deep-water, black argillite-chert-pillow basalt assemblage forming the Middle Ordovician Hood Bay Formation on southern Admiralty Island (Carter, 1977) indicates that the Admiralty subterrane developed back arc to the frontal Craig volcanic chain. The Admiralty back-arc setting was still volcanically active in the late Paleozoic, with regional deposition of the Retreat Group greenstones, locally incorporating Devonian/Mississippian-age reefal carbonates. The Middle(?) Devonian through Lower Permian stratigraphic

succession, constituting the Retreat Group and overlying Cannery Formation, appears to be more or less continuous on Admiralty Island. The Upper Devonian through Lower Permian Cannery Formation includes both an older, deep-water siliciclastic assemblage and a younger, shallow-marine chemical/clastic dolomite-chert facies (Loney, 1964). The Lower Permian Pybus Formation chert member signifies termination of back-arc sedimentation under shoaling conditions accompanying the amalgamation of Alexandria and Wrangellia. The welding together of these two juvenile oceanic settings may have imparted the penetrative  $S_1$  metamorphic segregation foliation that characterizes the Retreat Group.

The post-amalgamation unconformity ended with Middle to Late Triassic rifting related to the Nikolai plume. The Wrangellian Nikolai Greenstone and Admiralty Hyd Group flood basalt provinces overlap in time, although the Nikolai basalts are dominantly Carnian and the Hyd basalts Norian in age (fig. 3). As discussed in this paper, the Greens Creek ore deposit is hosted within Hyd Group rocks, specifically occurring at the base of the informal mine argillite member immediately underlying upper Hyd basalts. Conodont studies demonstrate that the mine argillite was deposited at the Carnian/Norian transition between 225 and 221 Ma (chap. 11). Following the Nikolai rifting event, a Jurassic-Cretaceous arc/trench system developed between the Wrangellian superterrane and the North American craton, accounting for the flysch of the Seymour Canal Formation and the Douglas Island Volcanics occurring on the eastern side of Admiralty Island. Arc/craton collision driven by eastward subduction along the leading Wrangellian foredeep culminated in mid-Cretaceous through early Tertiary Coast Range plutonism.

The prolonged period of late Mesozoic compressional tectonism, an expression of the Laramide in the northern Cordillera, led to polyphase deformation in the Greens Creek mining area. The dominant regional tectonic grain relates to  $D_2$  thrusting. That the Retreat Group and Cannery Formation lithologies are penetratively foliated by  $S_2$ , that mine argillite is isoclinally folded by  $F_2$ , but that upper Hyd Group flood basalts only show strong  $S_2$  development along their basal contact, indicates that the Upper Triassic deposits were ramped at relatively shallow crustal levels. Following the  $D_2$  overprint, the accreted complex was subjected to protracted transpression, giving rise to upright chevron-style  $F_3$  folding and related steeply dipping shear zones that strongly disrupt the regional  $D_2$  structural/stratigraphic framework. Reactivation of  $D_2$  thrusts post- $D_3$  produced shallow-dipping  $D_4$  shears that locally overprint  $S_3$ . Mid- to late-Tertiary dextral transform faulting along the Denali transform system, with major strands following Chatham Strait and Gastineau Channel, occurring respectively west and east of Admiralty Island, caused brittle  $D_5$  faults, such as the Maki system cutting through the immediate Greens Creek mine site. The similar orientations of  $D_3$ -ductile and  $D_5$ -brittle structures indicate that the  $D_3$  structural grain was reactivated in  $D_5$ . The late dextral fault strands locally develop complementary interior sinistral fault/fracture sets of minimal displacement.



**Figure 3.** Mine argillite exposed at mile 2.2 on the B-access road.

## Structural Framework within the Greens Creek Domain

The Greens Creek domain is defined as comprising the low-grade metamorphic assemblages which occur between major north- to northwest-striking shear zones bordering Hawk Inlet and Young Bay. Hyd Group rocks east of the Young Bay shear zone are at epidote-amphibolite hornfels facies, suggesting proximity to a Coast Range pluton such as the one mapped on the northeast corner of Admiralty Island. The mafic metavolcanic rocks occurring southwest of the Greens Creek thrust are overprinted by regional epidote-amphibolite facies metamorphism. These amphibolites may include amygdaloidal Retreat greenstones as well as Hyd-age metagabbro sills. The uppermost thrust forming the Cliff Creek headwall at the southeast corner of the map is a garnet-amphibolite facies. Recent U/Pb dates demonstrate the presence of Hyd-age metadiorite intrusions (S.M. Karl, oral commun., 2002). These garnet amphibolite gneisses are strongly injected by mid-Cretaceous(?) ferrodiorite and pegmatite dikes. The stacking of higher grade amphibolites structurally above the low-grade Greens Creek domain suggests that the area was strongly telescoped in a subductionlike setting typified by hot over cold metamorphic plates. The low greenschist facies domain hosting mineralization forms the structurally lowest plate, and the ambient metamorphic overprint within the Greens Creek domain is below biotite stability. Limited Ar/Ar work on white mica identifies a mid-Cretaceous age for the low greenschist facies metamorphic conditions (Brew and others, 1992; Haeussler and others, 1999).

The gross distribution of lithological units in the Greens Creek domain reflects dome-and-basin structural egg-crating. The prominent bluff of Retreat Group marble surrounded by Retreat Group greenstone that is shown in the central-northwest portion of the map area is identified as an  $F_2$  isoclinal preserved on the nose of an  $F_3$  anticline. The serpentinite-cored area of Retreat greenstone, extending westerly from the mine site through the Killer Creek drainage, is another basement high interrupting the Zinc Creek/Lil Sore Creek and Gallagher

Ridge tracts of mine argillite. The undifferentiated Cannery Formation sedimentary rocks on the eastern side of the map area and transected by the Young Bay shear zone form a subtly developed structural high. These domal elements are bordered by peripheral black phyllite. The more restricted tracts of mine argillite are tectonically imbricated with Retreat greenstone. In its regional context the Greens Creek domain comprises a window of complexly deformed low-grade phyllites exposed beneath Hyd flood basalts, forming nearly complete cover along the southern margin and a continuous belt along the northeastern boundary of the mapped area.

Tectonic imbrication, dome-and-basin interference patterns, and major northwest-trending faults collectively indicate that the area of the Greens Creek deposit has been subjected to polyphase deformation. There is evidence of five deformational events. The dominant penetrative  $S_2$  schistosity trends approximately east-west and dips moderately 20–40° south. An earlier  $S_1$  segregation foliation within Retreat greenstone forms isoclinal microfold closures in  $S_2$ . The thin-bedded mine argillite exhibits isoclinal  $F_2$  folding: spaced  $S_2$  cleavage in these rocks is axial planar to exceptionally appressed  $F_2$  folds, which are particularly well exposed at mile 2.2 on the B-access road and in the underground workings.  $S_2$  is more or less penetrative in all lithologies in the Greens Creek domain except for massive serpentinite, metagabbro, and the black dolomite beds, which occur within mine argillite. The ultramafic/mafic intrusions escaped this deformation through strain partitioning into marginal shears, while the black dolomite beds deformed brittlely, giving rise to ubiquitous ladder quartz veining (fig. 4).  $D_2$  accounts for the structural imbrication of the serpentinite-cored panels of Retreat greenstone north of the Killer Creek serpentinite body as the shallow to moderate, south-dipping lithological contacts paralleling  $S_2$  are clearly overprinted by high-angle  $D_3$  fabrics.

$D_3$  gave rise to northwest-southeast-trending shears and variably tight, upright, chevron-style folding of  $S_2$ . This fabric is only penetrative within the bounding Young Bay shear zone and the north-trending Hawk Inlet high strain zone.  $S_3$  intensifies along the numerous northwest-trending brittle/ductile fault zones. Most of the deformation along these topographic linear appears ductile, stress being accommodated largely by ductile stratal thinning rather than through brittle fault failure.  $D_4$  relates to late (post- $S_3$ ) low-angle shearing and intensifies southward toward the base of the thrust plates of amphibolite.  $S_4$  is rather common in the immediate mine area (for example, the Klaus fault), causing low-angle transposition of the steeply dipping  $S_3$  cleavage sets. It is notable that  $D_2$  thrusts and  $D_4$  shears both show broadly coincident orientation and vergence, suggesting reactivation of  $D_2$  thrusts late in the history of transpressional  $D_3$  shearing. All rocks have been displaced by late northwest-southeast-trending brittle faults showing dextral displacement—the Gallagher and Maki fault/fracture systems through the area of the mine show on the order of 1,000 and 1,800 feet of dextral west-side-up displacement, respectively. Complementary sinistral fault splays have only minor displacements; but where present, these make tracing geological units very difficult.



**Figure 4.** Convolute-folded black dolomite beds in massive sulfide, M120-S200 Ext. Photograph by N.A. Duke, University of Western Ontario.

## Tectonostratigraphic Assemblages

### Retreat Group

Three lithotypes are differentiated in the Retreat Group: greenstone, black phyllite, and marble. The only map-scale unit of Retreat marble is restricted to Limestone Bluff. Fossils collected by the USGS suggest that the marble is Silurian or Devonian (D.A. Brew, oral commun., 2002), which is consistent with the Middle(?) Devonian age assignment for this unit proposed by Lathram and others (1965). Limestone units occurring on strike to the north on the west shore of Hawk Inlet have been identified as Middle Devonian on the basis of recent conodont determinations (A.G. Harris, oral commun., 2001). The marble at Limestone Bluff is gray- to buff-weathering and composed essentially of coarsely crystalline calcite. Primary bedding is only weakly discernible, with buff dolomitic and siliceous layers slightly more resistant to weathering. Transecting shears weather brown and have limited quartz vein development. Lustrous gray to black phyllite forms thick units interlayered with the Retreat greenstones. That these monotonous “black shale” units have intimately interstratified greenstone panels suggests that they represent background sedimentation coincident with Retreat mafic volcanism. Also, like the Retreat greenstone units, these tracts of lustrous black phyllite retain no primary bedding features due to an intense  $S_1$  schistosity that developed prior to overprint by the regionally penetrative  $S_2$ -crenulation cleavage.

Units of Retreat Group greenstone are dominated by monotonous green chloritic phyllite with variable interlayering of lustrous gray phyllite after graphitic shale and rare thin gray to white marble bands. Retreat Group greenstone is without doubt the most enigmatic lithology in the district. This greenstone is everywhere characterized by streaky light/dark green layering of tectonic origin. The  $S_1$  overprint was so severe that neither flow nor intrusive contacts were observed. Rare relict amygdalites in samples collected north of Limestone Bluff, in the Lakes District, and at the west end of Gallagher Ridge

indicate a flow origin. Contacts with bordering units appear entirely tectonic; the streaky-foliated greenstone panels are structurally interleaved with gray phyllite and massive serpentinite. Greenstone contacts against graphitic units are strongly carbonatized. Contacts with interleaved serpentinites are extremely slivered, with greenstone/serpentinite sheeting on the meter scale. At the mine site, variably intense hydrothermal alteration of greenstone/serpentinite protoliths gives rise to voluminous mine phyllite in the stratigraphic footwall of the Greens Creek ore horizon (discussed herein and in Chap. 6). Limited geochemical work on Retreat greenstone broadly indicates that the protolith was compositionally similar to midocean-ridge basalt. Based on the present level of mapping, Retreat Group greenstone forms the primary flooring for the Hyd Group at the site of the Greens Creek mineralization. The  $S_1$  foliations indicate that this substrate was extremely tectonically attenuated prior to  $S_2$  deformation. The mine phyllite enveloping serpentinite may have been radically thinned at the time of serpentinite emplacement.

## Cannery Formation

Although the map shows the Cannery Formation as essentially undivided, the separate areas mapped as Cannery show marked lithological differences. The main domical exposure transected by the Young Bay shear zone is dominated by low-grade phyllites after core dolomitic arenite, medial dolomitic siltstone, and peripheral phyllitic chert. The outer phyllitic chert likely accounts for the on-strike cherty white phyllite units interleaved with black phyllite east of the mine. This same siliceous white phyllite accounts for the slaty siliceous sediments capping northerly trending spurs off the east-west-trending Gallagher Ridge of Hyd Group basalt south of the mine. These isolated white phyllite domains form klippen overlying the immediate mine stratigraphy at the Gallagher Creek headwall. This cherty white phyllite unit in the Greens Creek area is tentatively correlated to the Pybus Formation that caps the Cannery Formation regionally. Weathering of Pybus Formation accounts for common chert pebbles in basal Hyd Group conglomerate over Admiralty Island.

The metasedimentary rocks bordering on Retreat Group greenstone at Limestone Bluff are dominantly lustrous black and white siliceous schist. The more siliceous (cherty) units in this package form the prominent ridge crests paralleling Hawk Inlet. The Cannery Formation exposed along the shore of Hawk Inlet at the Cannery and along the A-road to Young Bay comprises varicolored gray-green-white-black banded schists, in part graphitic (black), in part marly (green) and in part dolomitic (white). The graphitic units are locally rich in nodular pyrite. The thin-banded character of these siliceous units is in part attributed to high  $D_3$ -strain overprinting a compositionally varied deep marine siliciclastic facies. This assemblage is interpreted as an older (Carboniferous?) component of the Cannery Formation. It is possible that some black phyllite now identified as Retreat Group sediment may include infolds of Carboniferous(?) siliceous rock. The Retreat “black schists” mapped

below the serpentinite of Killer Creek and the Mammoth Ridge green carbonate are strongly silicified, thus showing lithological similarity to the siliceous schists mapped as Cannery. The masking of lithotype by silicification is even more extreme in the Lakes District where considerable thicknesses of silica rock could be protolith in either Retreat black phyllite or the Cannery siliceous sedimentary rocks. The lower Cascade Creek section is somewhat transitional in lithology between Retreat phyllite and Cannery siliceous-graphitic-pyritic schist. This particular section is classed as Cannery on the basis that it is somewhat more lithologically varied than is typical for the units mapped as black phyllite of the Retreat Group.

## Serpentinite

The largest single serpentinite mass in the map area is the Killer Creek body, located 1.5 miles west-northwest of the mine site. This unit is strongly sheared on its upper and lower contacts against variably altered Retreat greenstone. Serpentinite-injected greenstone forming substrate to mine argillite is strongly carbonatized. The panel of Retreat greenstone in the immediate footwall of mine argillite is variably sulfidized, with pyrite-pyrrhotite-chalcopyrite forming patchy disseminations and locally massive replacement pods of meter scale. The northern contact of the serpentinite of Killer Creek has occasional talc-sericite-carbonate shears with associated zinc-lead-silver disseminations. The faulted southeast nose, exposed in Killer Creek at the B-road bridge, has associated massive magnetite-pyrite skarn mineralization.

Although the margins of the Killer Creek serpentinite are strongly deformed and mineralized, the interior is massive nonfoliated serpentinite. Limited microscopic study shows coarse honeycomb-textured serpentine outlined by the distribution of fine magnetite (up to about 10 modal percent). Ubiquitous disseminated magnetite in massive serpentinite accounts for coincident magnetic anomalies. The massive serpentinite of Killer Creek is a striking airborne magnetic anomaly, as are structural repeats at the mine site and in the upper reaches of Zinc Creek. However, serpentinite replaced by green carbonate (listwanite) is not magnetic, indicating magnetite breakdown during pervasive carbonatization. Extreme carbonatization of serpentinite is accompanied by formation of spaced waxy green foliations defined by barian mariposite. Limited microprobe work on green carbonate collected from Mammoth Ridge identifies paragenetically early magnesite and later species within the ankerite-kutnahorite solid solution series. Barite, barian mica, and barian feldspar species are also present. In some panels, like the one in upper Zinc Creek, green carbonate locally retains relict metagabbroic textures. Green micas in these domains are chromium-poor and barium-rich (oellacherite), indicating similar carbonate-barite replacement of the gabbroic injections into serpentinite. The best locale for demonstrating that sheeted gabbro dikes locally inject serpentinite is at Serpentine Gulch, the most northeasterly green carbonate body exposed on the Bruin Creek/Cub Creek ridge crest. Here, massive serpentine appears rather fresh, while numerous phases of

gabbro with preserved multiple chill margins are pervasively retrograded to green-brown mica, complex magnesium-iron-manganese carbonates, and pumpellyite (Reich, 1996). The mixed serpentinite/green carbonate sheet exposed in the uppermost tributaries of Lil Sore Creek shows considerable lithological affinity to the serpentine/gabbro complex at Serpentine Gulch.

In the more highly sheared and altered serpentinite/green carbonate sheets north of the main Killer Creek body there is ample evidence for structurally controlled talc-carbonate replacement of massive serpentinite. Toward sheared margins the massive serpentine becomes increasingly transected by brown carbonate fracture sets. Tectonic milling of serpentine blocks results in talc-carbonate schist enveloping “knockers” of massive serpentine. Within green-yellow talc schist, slips of green barian mariposite progressively replace serpentine smears. Talc-mariposite-barite veins crosscutting carbonated serpentinite and associated green carbonate are themselves deformed in  $S_2$ , clearly indicating that serpentinite emplacement/replacement predated regional  $D_2$  metamorphism. Common occurrence of green carbonate clasts in basal Hyd debriite (debriite is used here to connote debris-flow deposits, following Warme and Kuehner, 1998) conclusively ties serpentinite emplacement, alteration, and exposure to basal Hyd times. On the basis of detailed structural/stratigraphic evidence, the emplacement of serpentinite, with limited associated sheeted gabbro, can thus be linked to the initial stages of Hyd rifting. It is hypothesized that the serpentinite sheets were injected into growth faults that controlled the deposition of the mine argillite member of the Hyd Group.

## Black Phyllite

The extensive tracts of black phyllite that occupy the structural lows between the domains of Retreat greenstone and the Cannery metasedimentary rocks present a critical stratigraphic problem within the Greens Creek mining area. It is somewhat unclear to which unit they should be assigned; as mapped, they may include similar lithology of differing ages. The fact that the panels of Retreat Group greenstone are interlayered with panels of lustrous black phyllite indicates that black phyllite is a major member of the Retreat Group. However, that black phyllite also occurs peripheral to siliceous schist domains tentatively correlated with Pybus Formation suggests a black phyllite member that is younger than the uppermost member of the Cannery Formation. This problem is exacerbated by the difficulty of differentiating slaty to phyllitic facies of mine argillite from the more regionally extensive tracts of younger black phyllite. As currently shown on the map, the contact between black phyllite and mine argillite is a rather arbitrary boundary placed between (a) euxenic argillite with easily discernible black dolomite beds and (b) monotonous gray to black phyllite lacking recognizable bedding. At the current level of mapping, the tracts of undifferentiated black phyllite are considered primarily to postdate the Cannery Formation and, at least in part, to show stratigraphic

continuity with the mine argillite—the youngest black phyllite may occur on the weak sides and restricted mine argillite buttressing against fault blocks of Retreat greenstone on the strong downthrown sides of half grabens.

## Hyd Group

Unlike the Retreat Group and Cannery Formation in which detailed stratigraphy remains but poorly resolved due to complex regional metamorphic overprinting, the Upper Triassic Hyd Group, postdating the mid-Permian amalgamation of Wrangellia, can be clearly subdivided into basal growth fault-related breccia/debriite/conglomerate deposits, medial argillite, and upper basalt members. Other units include local argillaceous limestones at the base of the upper basalt and gabbro sills within medial mine argillite. Gabbro sill-argillite complexes occur below the upper Hyd basalts capping the Gallagher Ridge south of the mine, in the Lakes District, and in lower Lil Sore Valley south of Young Bay.

## Basal Hyd Group Breccia/Debriite/Conglomerate Deposits

The primary significance of the occurrence of extensive basal Hyd fragmental units is that these stratigraphically tie the Hyd Group to Retreat substrate. Most importantly, the lithological diversity of basal Hyd growth-fault-related rocks identifies the specific nature of the Hyd rift just prior to the deposition of mine argillite, host to the high-grade Greens Creek ores. The deepest seated manifestation of growth-fault lithotypes comprises 10–100-meter-thick zones of silicified mylonite (mapped as Trhsr—siliceous rock) closely affiliated with carbonate-altered serpentinite. There is a semicontinuous siliceous band striking from the immediate mine site along the length of Mammoth Ridge. The silicified rock delineating this structural unit is derived primarily through intense silicification of greenstone protolith, accounting for finely disseminated leucoxene. Not shown are associated alteration zones grading outward from siliceous rocks into tan sericite-leucoxene phyllite, sericite-chlorite-ankerite phyllite, and chlorite-calcite phyllite into greenstone. These various hydrothermal alteration zones overprinting Retreat greenstone collectively make up the mine phyllite occurring in the stratigraphic footwall of the Greens Creek ore deposit. As this zoning is best developed at the mine site, it is described in more detail in the section below on mine geology. The silica rock that forms a series of benches in the Lakes District is thought to represent a major sheet of silicification related to the emplacement of the Killer Creek serpentinite.

By far the best exposures of basal fault-breccia and debriite are found in outcrops following Zinc Creek and forming a near-continuous unit extending northeast along the Lil Sore drainage. The best development of nonbedded fault breccia is in the lower and middle reaches of Zinc Creek. These

areas are dominated by massive heterolithic phyllite breccia protolithed wholly in mine phyllite and green carbonate-altered serpentinite. The fact that no fresh greenstone and only rare serpentinite clasts are observed in these breccias, despite their provenance in greenstone/serpentinite-altered equivalents, unequivocally links the formation of basal Hyd fault breccia to hydrothermal alteration of active fault structures controlling the deposition of mine argillite.

The first appearance of mine argillite clasts in fault breccia approximates the transit from poorly layered breccia to bedded debriite. Significantly, the most readily identifiable mine phyllite clasts in bedded debriite tend to be the most highly altered sericite-mariposite phyllite and green carbonate clasts. The matrix of debriite adjacent to basal mine argillite is typically crystalline quartz-carbonate, signifying a hydrothermal silica-dolomite cementing agent. Nodular pyrite, with or without barite, is relatively common. The contact between basal Hyd debriite and medial Hyd mine argillite is placed at the transition from dolomite-clast debriite, which comprises cryptocrystalline black dolomite clasts in a crystalline carbonate matrix, to coherently bedded black dolomite interlayered within slaty black pyritic argillite. North of the Zinc Creek/Lil Sore Creek divide, resedimented argillaceous grit overlies non- to poorly layered mine phyllite pebble debriite. The unit of Hyd Group conglomerate (Trhc) traced from exposures on the A-road southeasterly to the mouth of Lil Sore Creek on Young Bay is also poorly layered but contains a greater variety of clasts—the red jasper clasts are weathered from Pybus Formation while the green carbonate clasts indicate a source in mine phyllite. The Hyd conglomerate unit shown at the headwall of Greens Creek separates black phyllite and Hyd flows; that is, no mine argillite is recognized at this locale. This particular conglomeratic unit includes upper Hyd Group basalt clasts, indicating that deposition postdated the initiation of the flood basalt volcanism.

## Restricted Mine Argillite Troughs

The occurrence of well-bedded black argillite/black dolomite overlying debriite deposits of the same lithological makeup conclusively ties mine argillite stratigraphically to the basal Hyd Group fault-controlled breccia/debriite/conglomerate deposits. Using dolomite beds as a defining characteristic of mine argillite restricts its distribution to (1) the faulted margins against altered Retreat greenstone (mine phyllite) and (2) the immediate base of upper Hyd flood basalt. At the mine, the high-grade laminated zinc-lead-silver ores form a basal mine argillite facies that immediately overlies massive white carbonate-barite ores capping mine phyllite. Here, the well-bedded mine argillite overlies only minor basal Hyd fault breccia/chert conglomerate, indicating the juxtaposition of a coherent panel of intensely hydrothermally altered Retreat greenstone almost directly against slump-folded mine argillite.

In the Zinc Creek trough, the Greens Creek ore horizon occurs well below the base of coherently bedded black dolomite interlayered with pyritic slaty argillite. Given the setting

at the mine site, ore should occur below the first appearance of black dolomite clasts within debriite stratigraphy. Thin (decimeter scale) black dolomite interbeds persist vertically through mine argillite even where this unit is apparently thickest, as in the Lil Sore Valley and on Gallagher Ridge. That no significant mineralization is known to occur much above the basal contact suggests that hydrothermal activity and ore deposition coincided with the collapse that initiated restricted trough-controlled mine argillite sedimentation.

The upper termination of mine argillite is represented by a thin, discontinuous argillaceous limestone member deposited immediately below the upper Hyd flood basalts. Conodont specimens from basal ores to the capping limestone identify a relatively short time span for mine argillite deposition ( $220.7 \pm 4.4$  Ma, chap. 11). The variable yet considerable thickness of mine argillite (locally up to a few hundred meters) may be attributed to chemical precipitation within hydrothermally active troughs keeping pace with tectonic subsidence; that is, the host mine argillite to the Greens Creek ore may represent a highly reduced hydrothermal brine pool lithofacies.

## Upper Hyd Group Gabbro Sills/Flood Basalts

The Greens Creek District includes only the basal members of the upper Hyd Group: the gabbro sills intruding into the medial Hyd mine argillite and the immediately overlying, similarly metagabbroic-textured massive flows, flow breccias, and minor pillow basalt. Intense swarms of gabbro sills intrude white phyllites (a Pybus equivalent?) in upper Cliff Creek and mine argillite south of the mine, in the Lakes District, and in Lil Sore Valley. These gabbros are medium grained and nonfoliated and exhibit relict gabbroic to diabasic textures. They are completely hydrated, being composed essentially of uralitized pyroxene and saussuritized plagioclase. The limited petrographic work carried out to date has not identified any relict primary pyroxene or plagioclase. Observed fining of grain size toward sill margins indicates that the secondary mineralogy faithfully pseudomorphs the primary igneous textures. The massive metagabbroic units overlying mine argillite in the Lakes District are fine to medium grained and could include massive flows capping the medial Hyd argillite. Upper Hyd flows capping Gallagher Ridge and traced to the headwall of Cliff Creek immediately overlie a discontinuous limestone unit occurring at the top of the mine argillite. These may show the same metagabbroic textures as the sills into underlying mine argillite but are retrograded to greenschist facies chlorite-albite-calcite mineral assemblages. The Hyd Group basalts of upper Cliff Creek are dominantly flow breccias. Rare pilowed flows in the lowermost volcanic units indicate initial eruption into locally submarine conditions. Hydrothermal breccias crosscutting the basal flows have associated minor chalcopyrite-pyrite mineralization.

Little information is presently available for the superjacent garnet amphibolite facies mafic gneisses in upper Cliff Creek. The boundary between the greenschist and amphibolite facies rocks is a sharp, moderately south-dipping thrust

surface along which amphibolitic gneisses are juxtaposed over greenschist facies metavolcanics. The amphibolitic gneisses are characterized by metamorphic layering and common ferrodiorite and pegmatite diking. Only one dike of ferrodiorite was observed on the Gallagher Creek headwall below the Cliff Creek thrust. Notably, similar ferrodiorite dikes have also been intersected locally in the underground mine workings where they clearly crosscut  $S_2$ , but both inject and are overprinted by  $D_3$  cleavages. The relation of the garnet amphibolite facies gneisses at the base of the Cliff Creek thrust to epidote-actinolite amphibolite occurring at the base of the central Greens Creek thrust is unknown. The strong airborne magnetic anomaly associated with this latter boundary may relate to basal serpentinite and(or) a pyrite to pyrrhotite metamorphic conversion.

## Mine Site and Prospect Geology

Bedrock exposures at the Greens Creek mine site are limited, and the specific geological setting of the ores is best deciphered on the basis of underground mapping and drill sections. Only features that place the mineralization within the regional structural/stratigraphic framework and bearing most directly on the origin of the high-grade ores are considered here. Following a brief review of the mine-site geology, selected known mineral prospects are described to illustrate the metal endowment of the district as a whole.

The Greens Creek ore horizon outcrops near the eastern nose of Retreat greenstone cored by the Killer Creek serpentinite. This nose of greenstone is intensely altered, forming mine phyllite proximal to the mineralization. The host structure has the geometry of an  $F_2$  anticline. Given the subtle but significant change from structurally lower mine argillite to structurally overlying black phyllite on the limbs, it is possible that the core of greenstone may have originated as a basement horst, sidewall to a mine argillite trough. Cross-folding causes marked structural egg-crating and accounts for symmetrical hour-glass pinchouts of the immediate mine stratigraphy on the opposing limbs. The Greens Creek ores are specifically sited on the overturned eastern limb. Offsets postdating  $F_3$  folding caused by the Klaus and Maki fault systems severely hamper stratigraphic reconstructions. Nevertheless, the detailed exploratory work clearly demonstrates that ore is confined to the immediate mine argillite/mine phyllite contact. The Greens Creek ore horizon is sandwiched between structural-hanging-wall mine phyllite, derived from hydrothermal alteration of Retreat greenstone, and structural-footwall mine argillite, on the lower overturned  $F_2$  fold limb. The original host-rock stratigraphy had mine argillite deposited against pervasively hydrothermally altered Retreat greenstone (the mine phyllite). Mine phyllite comprises chlorite-calcite phyllite, chlorite-sericite-ankerite phyllite, tan sericite-leucoxene phyllite, and silica rock developed through increasingly intense hydrothermal alteration of an already  $S_1$ -foliated greenstone protolith, as well as

green barian mariposite-talc-carbonate-barite phyllite developed through alteration of serpentinite and lesser gabbro.

At the mine portal, mine argillite is separated from the mine phyllite by a thin interval of dolomitic phyllite/cherty dolomite. This assemblage has lithological kinship to the white phyllite occurring south and west of the mine and is tentatively correlated with the Cannery Formation (PDcpw on plate 1). Both underground and surface drilling have commonly intersected impure dolomitic to phyllitic cherts below a persistent black and white banded chert marker. Where this impure chert/dolomite sequence stratigraphically underlies the high-grade ores, it carries appreciable pyrite and may contain up to 2 percent zinc. Massive bodies of white dolomite-barite, capping mine phyllite and at least partly derived through hydrothermal replacement of greenstone protolith, can locally constitute high-grade zinc (20 percent), lead (8 percent), silver (20 troy ounces per ton), and gold (0.5 troy ounce per ton) "White Ore." The very high-grade zinc (30 percent), lead (10 percent), and silver (>50 troy ounces per ton) laminated "Black Ore" occurs at the base of anoxic graphitic argillite peripheral to massive, non- to poorly bedded "mounds" of frambooidal textured pyrite. The highest grade ores are essentially restricted to the base of the mine argillite. Immediately above ore, the mine argillite is characterized by dense, cherty, black dolomite interbeds that are moderately manganeseiferous (2 percent  $MnO_2$ ). Away from mineralization, the host mine argillite tends to be limy rather than graphitic and dolomitic, suggesting waning of hydrothermal input away from zones of discharge.

The stratigraphic position of the Greens Creek ores at the Retreat Group/Hyd Group contact places the site of the mineralization at the regional mid-Permian to Upper Triassic unconformity. Where preserved, the footwall cherts are commonly hydrothermally silicified and brecciated and are locally conglomeratic. These sometimes-graded chert pebble beds represent erosional lags of the Pybus Formation and therefore identify the basal Hyd unconformity. The affiliation of silicified conglomerates with limited, growth-fault-controlled mine phyllite breccia indicates that Greens Creek mineralization accompanied the initial collapse of the Hyd rift, the deposition of the overlying high-grade black ores coinciding with restricted marine incursion.

## Prospects in the Greens Creek District

A number of prospects have been discovered during ongoing surface exploration efforts in the Greens Creek district. The following brief descriptions of selected targets illustrate the character of mineralization away from the immediate mine site. Prospects are listed from the south extension of the land exchange northward; the primary aim is to situate various mineralized sites within their local geological environment.

## Upper Cliff Creek

Mine argillite underlies the upper Hyd basalt in the headwall of Cliff Creek. Numerous Hyd gabbro sills are injected into white cherty phyllite immediately below argillite. Geochemically anomalous but weak sulfide mineralization is associated with the sill margins. The absence of footwall mine phyllite after altered Retreat greenstone suggests that this is a distal, non-fault-controlled contact where the mine argillite onlapped Pybus Formation.

## Gallagher Creek

The Gallagher Creek area overlies the downdip extension of the mine (fig. 5). Just as the Maki fault cuts through the underground workings, the Gallagher fault system cuts through the Gallagher Creek area. The mineralization exposed in lower Gallagher Creek consists of pyrite-pyrrhotite-sphalerite-impregnated mine phyllite. This is interpreted as footwall alteration to the Greens Creek ore horizon. Polymetallic sulfide mineralization occurs within the isoclinal  $F_2$  infold of mine argillite overlying a substantial thickness of basal Hyd debriite. This is identified as a structural repeat of the Greens Creek ore horizon. The Gallagher infold occurs immediately below a shallow, south-dipping, late  $D_2$  thrust in central Gallagher Creek. The upper-plate rocks consist of black phyllite and sericitic siliceous sediment, which is in turn overlain by gabbro-silled mine argillite and the upper Hyd basalt flows, forming the ridge crest. Lithologies making up the upper plate are broadly correlative to the Cliff Creek section.

## West End

The West End prospect is at the western termination of the prominent Gallagher Ridge southwest of the mine. At West End, mine argillite overlies a thin interval of debriite developed on a serpentinite-plumbed panel of mine phyllite. Though structurally thin, the upright mine argillite/mine phyllite section at West End is basically lithologically similar to the overturned section hosting the Greens Creek ore.

## Cub Creek/Lower Bruin Creek

Mine phyllite structurally overlies mine argillite between Cub and Bruin Creeks, the same overturned structural/stratigraphic setting as the mine (fig. 6). Anomalous geochemistry and evidence of growth-fault breccia at the phyllite/argillite contact are positive indicators for occurrence of Greens Creek type ores.



**Figure 5.** Hyd Group basalt capping the South Ridge at the headwall of Gallagher Creek.



**Figure 6.** Surface drill site in upper Cub Creek.

## Upper Bruin Creek/Mammoth Ridge

The Mammoth Ridge green carbonate and related mariposite phyllite association represents the most highly altered ultramafic/mafic rocks in the district. This rock package has considerable lithological similarity to California Mother Lode-type gold systems. Despite the intensity and magnitude of alteration, the adjacent mine argillite is less “sooty” and more “phyllitic” than the host argillite at the mine site. A possible explanation is that Mammoth Ridge was a topographic high at the time of fluid expulsion and is juxtaposed against argillite deposited stratigraphically above or lateral to the restricted sooty facies of argillite hosting the ore.

## Mammoth Pyritic Massive Sulfide Deposit

The Mammoth pyritic massive sulfide deposit is hosted in lustrous black schist immediately below the green carbonate altered serpentinite that extends the length of Mammoth Ridge (fig. 7). Bands of massive pyrite interleaved with schist are exposed over about 200 feet of elevation, with the central 50 feet of the interval dominated by massive pyrite bands of meter scale. These central bands are the most massive and have the finest grained textures. Grab samples reveal chalcopyrite-rich breccia clasts in pyrite-quartz-barite gangue. Like the Greens Creek deposit, the Mammoth deposit is intersected by the Maki fault system (fig. 8). Although more highly recrystallized, the Mammoth pyrite deposit may be akin to the barren pyrite centers developed within the Greens Creek deposit.

## Killer Creek

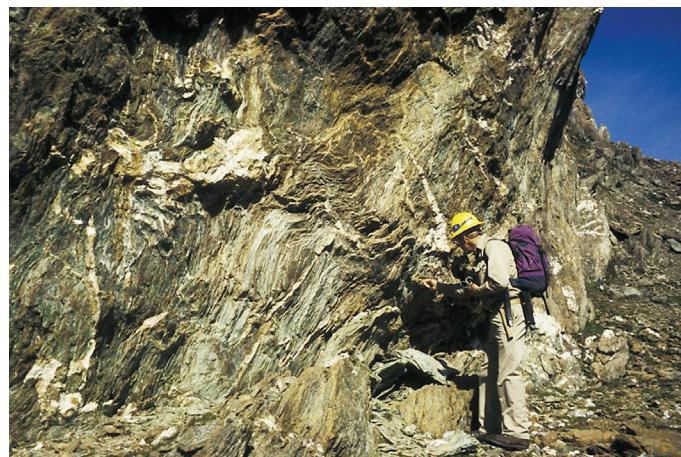
The Killer Creek serpentinite is a south-dipping sheet overlying strongly sulfidized chlorite phyllite developed from Retreat greenstone (fig. 9). Local zones of sericite-talc phyllite with patchy sub-ore grade silver values lie along this basal contact at surface. However, mapping has yet to identify host mine argillite in the section. Exploratory work suggests a footwall feeder system with the serpentine mass occurring where the Greens Creek ore zone would be expected.

## Cascade Creek

Several zinc prospects are in the Cascade Creek drainage. These take the form of patchy disseminations of sphalerite along phyllite/greenstone contacts. The sphalerite mineralization has been overprinted by  $S_2$  foliations, suggesting zinc remobilization into the strongly  $S_1$ -sheared margins of greenstone units bordering on graphitic-pyritic phyllite. These contacts tend to be strongly carbonatized, silicified and, more locally, sulfidized. The occurrence of stringery sphalerite in this environment suggests that the Retreat black phyllite/greenstone association is a preferred reservoir for the Greens Creek pay metals.

## Lakes District

Extensive stockwork mineralization occurs in strongly brecciated quartz-graphite schist below gabbro-silled mine argillite at the northwest termination of the Killer Creek serpentinite in the Lakes District. Mineralization includes veinlets of pyrite-sphalerite-chalcopyrite and patchy, semi-massive, coarsely granular aggregates cemented by galena-sphalerite-tetrahedrite. Well-mineralized samples have also been collected from the immediate contact of the mine argillite overlying mine phyllite. Anomalous zinc-lead-silver is associated with overlying gabbro sill/argillite contacts. The Lakes District is a prime target for the preservation of a satellite Greens Creek-type deposit.



**Figure 7.** Examining green carbonate on Mammoth Ridge.



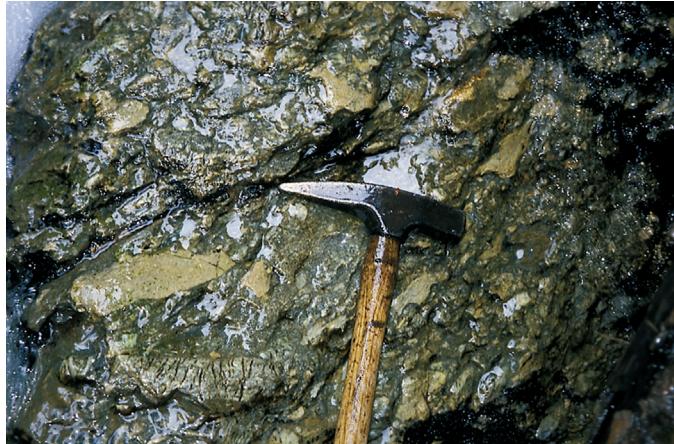
**Figure 8.** The trace of the Maki fault system north of Gunsight Pass.



**Figure 9.** Silicified rock developed below the Killer Creek serpentinite.

## Zinc Creek

As the name indicates, the Zinc Creek drainage is characterized by anomalously high zinc in stream geochemical surveys. The creek cuts across the southern culmination of the Zinc Creek/Lil Sore Creek trough of mine argillite. In lower Zinc Creek, thick phyllite breccia capped by heterolithic debriite underlies strongly sulfidic mine argillite (figs. 10, 11), with meter-scale intervals containing 30 to 40 percent laminated pyrite with associated barite. This facies of argillite is lithologically identical to mineralized slaty argillite in the mine stratigraphy. Underlying crystalline-carbonate cemented debriite is also sulphidic with trace to minor disseminated chalcopyrite. In places, the debriite is wholly replaced by crystalline carbonate-barite lithologically similar to dolomitic massive argillite hosting white ores in the mine series.



**Figure 10.** Basal Hyd Group phyllite breccia exposed in upper Zinc Creek.



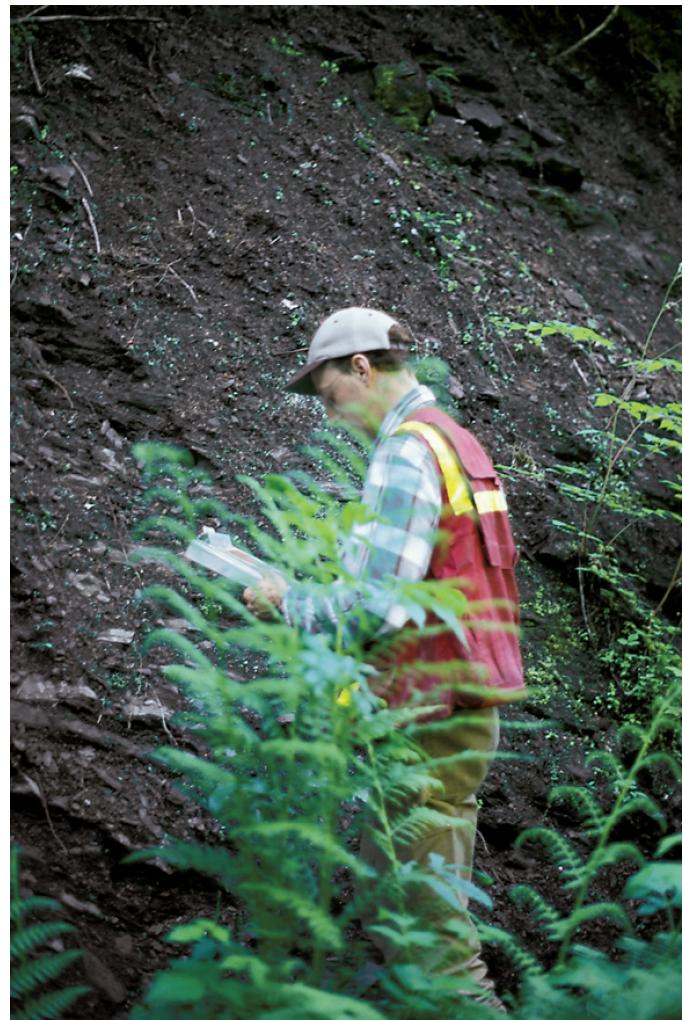
**Figure 11.** Basal Hyd Group heterolithic debriite exposed in lower Zinc Creek.

## Lil Sore Creek

The mine argillite/phyllite breccia contact in lower Zinc Creek extends northward into argillite/phyllite debriite following the Lil Sore drainage (fig. 12). Like Zinc Creek, Lil Sore Creek is geochemically anomalous, attributed to the fact that this stream course runs along the basal argillite/debriite contact. Geochemical sampling surveys carried out over the Lil Sore mine argillite trough also identify weak sulfide mineralization related to gabbro sills in argillite well above the basal contact.

## A-Road Barite

This roadside outcrop exposes a baritic chert horizon occurring near or at the contact between quartz schist and very highly sheared black phyllite. A strongly carbonatized gabbro sill intrudes the immediate contact. This prospect may be a baritic member of the Pybus Formation or mark the distal tail-end of the Greens Creek ore horizon.



**Figure 12.** Examining mine argillite exposed in Lil Sore Creek.

## Metallogeny

Although the high-grade Zn-Pb-Ag-Au-Ba ores at Greens Creek are similar to Kuroko-type volcanogenic massive sulfide (VMS) deposits, and the mine is located in an island arc system, the absence of associated felsic volcanics argues against any direct application of a Kuroko-VMS model. Similarly, although the metal signatures at Greens Creek are also consistent with shale-hosted sedimentary-exhalative (SEDEX) mineralization of the Mount Isa type, application of the model is made problematic by the juvenile arc setting at Greens Creek—SEDEX mineralization is generally held to relate to intercontinental to continental-margin rift settings. Based on the foregoing overview of the regional geological setting and of the deposit itself, it is here proposed that Greens Creek is a unique type of polymetallic sulfide mineralization, with the ores being essentially SEDEX in origin but linked to rifting within a juvenile arc system.

The most unusual feature of the immediate host-rock stratigraphy at Greens Creek is the evidence it presents for a 150-Ma time gap between the origin of the Retreat greenstone, protolith to mine phyllite, and the deposition of polymetallic ores at the base of the mine argillite. This time gap may be attributed to uplift of the Retreat Group after deposition of the Lower Permian Pybus Formation, accounting for the occurrence of chert pebble conglomerates below the Upper Triassic zinc-lead-silver-gold ores. These lag deposits represent the weathering of the Pybus Formation cover sequence. The absence of the full Cannery Formation at the mine suggests that the site of mineralization may have been a mid-Permian high, with uparched Retreat greenstone being onlapped only by impure dolomitic cherts capping the Cannery Formation regionally.

The ongoing conodont dating program of mine argillite has confirmed that the Greens Creek ore was deposited at  $220.7 \pm 4.4$  Ma at the Carnian/Norian transition (chap. 11). This age, falling between the Carnian-age Nikolai flood basalts in Wrangellia and the Norian-age Hyd flood basalts in Alexandria, is key for linking arc rifting to the effects of the Nikolai plume. The thinness of juvenile back-arc crust may account for the association of Greens Creek ore with massive serpentinite. Serpentine emplacement is intimately associated with dewatering along growth-fault structures that controlled deposition of the mine argillite. There is a strong spatial relationship between the serpentinite sheeting and the wholesale hydrothermal alteration of Retreat greenstone to mine phyllite. Occurrence of footwall mine phyllite breccia and debris deposits irrefutably ties the host mine argillite stratigraphically to altered Retreat Group greenstone substrate. The green carbonate clasts developed from altered serpentinite, which are common in basal Hyd phyllite breccia/debrite units, indicate that the serpentinite must have (a) been present in the controlling growth-fault structures, (b) participated in fault-focused hydrothermal alteration, and (c) been exposed on fault scarps prior to ore deposition. More study is needed to address the origin of the associated serpentinite and its function in fluid evolution. Certainly the widespread occurrence of barian mariposite in green carbonate altered serpentinite ties this

alteration to the baritic replacement ores hosted in footwall mine phyllite. The similarity of this green carbonate to that occurring in the California Mother Lode mesothermal gold district is striking—so much so, in fact, that one wonders if the Greens Creek ores could in some fashion be a surface manifestation of a mesothermal gold system at depth, perhaps in some way accounting for its richness in precious metals.

At Greens Creek, the host mine argillite overlies massive crystalline barite-carbonate bodies developed in part by hydrothermal replacement of mine phyllite; these bodies locally comprise white ores. The occurrence of such ores low in a mineralized system capped by stratiform high-grade black ores with the same metal signature strongly suggests that the ores formed proximally within an environment of active hydrothermal venting. The fact that the stratiform ores were deposited at the base of a considerable thickness of anoxic black argillite interlayered with thin dolomite beds indicates that they represent initial deposits related to marine inundation of restricted, hydrothermally active trough environments at the time of rift collapse. The widespread occurrence of growth-fault breccia and debrite signifies considerable mass wasting from hydrothermally altered fault scarps prior to mine argillite deposition. The evidence thus points to hydrothermal fluid expulsion in a dynamic growth-fault-controlled depositional regimen. Fault control is clearly indicated by the fact that the Greens Creek ore horizon coincides with a “silica rock” structural marker that extends from the mine site for several kilometers and runs the length of Mammoth Ridge. Farther north, in the Zinc Creek/Lil Sore Creek trough of mine argillite, this same structural/stratigraphic position is occupied by considerable thicknesses of phyllite breccia and debrite, indicating preservation of the surficial “depositional” growth-fault environment.

Both mine phyllite and the related phyllite breccia/debrite deposits are locally replaced by siliceous dolomite variably rich in pyrite and barite. This “hydrothermal dolomite” may have kinship to footwall copper orebodies that accompany several large SEDEX deposits, suggesting that yet undiscovered copper ores may well occur deeper in the Greens Creek system. The debrite deposits themselves are cemented by crystalline carbonate and zones of quartz-pyrite-ankerite-barite, indicating dynamic hydrothermal plumbing. Primary hydrothermal textures are common in the overlying stratiform ores as well. Porous-textured frambooidal pyrite forming massive centers of mineralization is variably recrystallized into compact euhedral forms. Analytical work reveals that the most primitive porous pyrite species coexisting with colloform sphalerite and galena are enriched in arsenic-antimony-silver-gold (Bennett, 1999). Perhaps some form of zone refining of both precious and semiprecious metals toward the margins of growing frambooidal pyrite mounds was instrumental in concentrating the unusually high grade zinc-lead-silver ores. To what extent recrystallization was induced by heat buildup due to capping of the hydrothermal system and to what extent it is related to the Late Cretaceous metamorphic overprint has yet to be determined. The Greens Creek ores have certainly not undergone complete metamorphic

recrystallization since they retain many original depositional textural features. Nevertheless, some features of the deposit are best accounted for by secondary remobilization during metamorphic and later structural overprinting. In particular, the erratic distribution of the ruby silvers and of silver-rich electrum signifies marked precious metal mobility.

## Conclusion

Geological mapping in the Greens Creek district broadly supports a dynamic growth-fault-controlled depositional environment for the Greens Creek ores. The specific contact relationships within the immediate mine stratigraphy are subject to dynamic change. Adjacent Retreat greenstones may show no hydrothermal alteration, altered contacts have been subjected to variable mass wasting, and the basal “sooty” facies of mine argillite is commonly missing. It seems probable that the high-grade stratiform ores represent the front of an anoxic marine transgression into dynamic restricted trough settings. The ores ponded against hydrothermally active fault scarps plumbled by serpentinite accompanied by limited sheeted gabbro diking. The serpentinite and gabbro dike association suggests development of active igneous fissure segments at the inception of Late Triassic rifting. The Killer Creek serpentinite body may have provided a sustained heat source within uparched Retreat Group greenstone essentially denuded of its Permian-Carboniferous cover. In contrast to classic SEDEX systems, the Greens Creek setting is therefore one in which “igneous” heat may have had a more formative function in driving a dynamic hydrothermal fluid cell, perhaps initiating a component of fluid recharge from surface, above and beyond discharge of formation brine. That the Greens Creek ores occupy the profound regional mid-Permian to Late Triassic unconformity that characterizes the geological record on Admiralty Island suggests that the Greens Creek fluid reservoir may well have tapped evaporitic brines from the surface.

## Acknowledgment

This chapter benefited from constructive reviews by Sue Karl and David Brew.

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